Bending and compression characterization of hollow structural elements made of recycled Tetra Pak®-Based Boards (RTPBB) and an approximated calculation of the carbon footprint involved in their production

Caracterización de la flexión y compresión de elementos estructurales huecos fabricados con láminas de Tetra Pak® reciclado y cálculo aproximado de la huella de carbono producida en su elaboración

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Abstract

The present research summarizes the test results of mechanical capacity of built-up structural elements, intending to introduce the possibility of using RTPBB as material for creating structural solutions for temporary housing, and for small houses. Hollow columns and beams models helped in understanding theoretical behavior by using nonlinear stress-strain relations of the material, and finite element models (FEM) to determine the areas where stresses and deformations are principal. Optimum thickness boards of about 15mm helped to build the specimens, which afterwards were failed using and MTS testing machine, following monotonic loads. Tests performed, mainly focused on compression and bending, using hinged supports and a central two-points-loading arrangement respectively. Additionally the research presents a basic comparison of mechanical results to those reported by technical manuals of commercial plywood in Colombia. In a parallel analysis, a functional unit defined, helped in the estimation of the carbon dioxide footprint equivalent for various steps of the production processes of the base material. Results show that although the RTPBB has a low elastic behavior, stresses remain below the ultimate stress. Column failure tends to be brittle compared to that failure for the bending resistant elements. However, the presence of local buckling suggests also the means needed to improve said capacity. Failure loads are similar to those reported for commercial plywood in Colombia, however, experiencing larger deformations. The carbon footprint was determined to be reduced about 20% (production of the material used in this research), compared to commercial plywood material in Colombia.

Keywords: *TetraPak based boards, hollow structural elements, mechanical properties of plywood, carbon footprint, eco-materials*

Resumen

Este trabajo resume los resultados de los ensayos sobre la capacidad mecánica de elementos estructurales construidos, con la intención de introducir el uso de las láminas de Tetra Pak® reciclado como material para la creación de soluciones estructurales destinadas a viviendas temporales y de tamaño pequeño. Se usaron vigas y columnas huecas como modelo las que ayudaron a comprender el comportamiento teórico, mediante relaciones tensión-deformación no lineales del material y modelos de elementos finitos (MEF) para determinar las principales áreas dónde se produce la tensión y deformación. Las muestras se fabricaron con las láminas de 15mm, un espesor óptimo; luego se sometieron a falla usando una máquina de ensayo MTS, con cargas monotónicas. Para los ensayos realizados, enfocados principalmente a la flexión y compresión, se usaron apoyos articulados y un dispositivo central de carga en dos puntos. La investigación presenta además una comparación básica entre los resultados de los ensayos mecánicos realizados con los descritos en los manuales técnicos para madera laminada colombianos. Un análisis paralelo, con una unidad funcional definida, ayudó a estimar la huella de dióxido de carbono equivalente para las diversas etapas del proceso de producción del material de base. Los resultados muestran que a pesar de que la lámina de Tetra Pak reciclado tiene un comportamiento elástico menor, las tensiones se mantienen bajo la tensión última. La falla en la columna tiende a ser frágil comparada con aquella de los elementos resistentes a flexión. Sin embargo, la presencia de pandeo local sugiere también los medios para mejorar dicha capacidad. Las cargas para falla son similares a las informadas para la madera laminada colombiana, sin embargo, presentaron mayores deformaciones. Se determinó que la huella de carbono se redujo en un 20% (para la producción del material utilizado en esta investigación) en comparación con el producido para fabricar la madera laminada comercial en Colombia.

Palabras clave: Láminas de Tetra Pak reciclado, láminas en base a Tetra Pak, elementos estructurales huecos, propiedades mecánicas de la madera laminada, huella de carbono, materiales ecológicos

1. Introduction

A big challenge for civil engineering nowadays is to procure for the development of a construction material that is both sustainable and resistant. In addition, if with said material designers can explore structural members for temporary houses allowing them to re-use them, as many times as possible, then, it is met the goal of a sustainable temporary housing solution Arslan (2007). This was the motivation towards a mechanical characterization of a series of TetraPak® based structural members, improving the previous mechanical knowledge of a series of tensile tests performed in the past by the fabricant. At the same time, a basic analysis for the environmental impact of its production in terms of carbon dioxide footprint was important to account production impacts on the environment.

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These boards are under production worldwide. TetraPak® has fostered its use through Europe, especially in Germany where they achieved a 69% recycling of the produced containers. The Chinese agency for environmental protection accepted in 1997 this material as a recommended national technology towards environmental protection Chung (2003) and the following year the same material was pointed as a sustainable and reliable construction material by the National Committee for Science and Technology Betancourt-García (2009). Its primary use is still nowadays to create furniture pieces. The TetraPak®-based boards used in the present research are characterized by their high capacity to humidity, impact and temperature, the later one specially because the thermal degradation range is among 210 and 470°C, Figen et al. (2013) and comparable thermo-acoustic and thermo-foldable characteristics.

The production process starts with all the cardboard being removed by shredding and refinement of the original TetraPak containers. The remaining polymeric-based material and the aluminum parts of TetraPak (named poly-aluminum) is weighted proportionally 75% -25%. This material goes into a mill for crushing and refinement R.-I. RIORION-Ltda (2005), following a standard procedure for mechanical recycling of solid plastic waste Kim and Van Geem (2017). The produced particles are in sizes in the range of 3 to 5 mm. Then, a task of compaction process follows where the loose particles remain extended over flat surfaces that compress the material as it is heated. The result is the boards used in the present research. The polymeric part of the material works as the confinement matrix for the aluminum particles. As a final part of the process, boards experience a cooling environment at -4°C to stiffen the material. Boards then are ready to cut according to customer's needs. A schematic of the process is available in Figure 1.

According to previous research performed by the local company that produces these boards, the basic mechanical behavior of the TetraPak® based material is similar to that of a three-layered polymeric-stiffened plywood product found in Colombia for construction purposes R.-I. RIORION-Ltda (2005).

Tests performed in a recent study for the same type of material, show a semi-nonlinear behavior, even for expected elastic behavior at small deformations in bending Carrillo et al. (2014). The main difference with said study and the present one is the magnitude of the specimens used in bending. According to said reference a 24:1 thickness-to-cross-section ratio should be used to find the modulus of rupture and apparent modulus of elasticity ASTM D1037 (2012). However, for the present research, a real structural element was the scope of tests, where this ratio was about 10.

Table 1 shows the average mechanical parameters reported for a Colombian commercial RTPBB product (Ecoplak), in comparison with a typical wooden-based board, both compared having as reference the NTC-2261 Colombian code of production for boards made of agglomerated particles for non-structural applications I. C. de N. T. y C. (ICONTEC) (2003). These parameters were important as a reference for the RTPBB and wooden-based FEM comparison models. These parameters show how this type of material has comparable qualities to wooden-based materials.

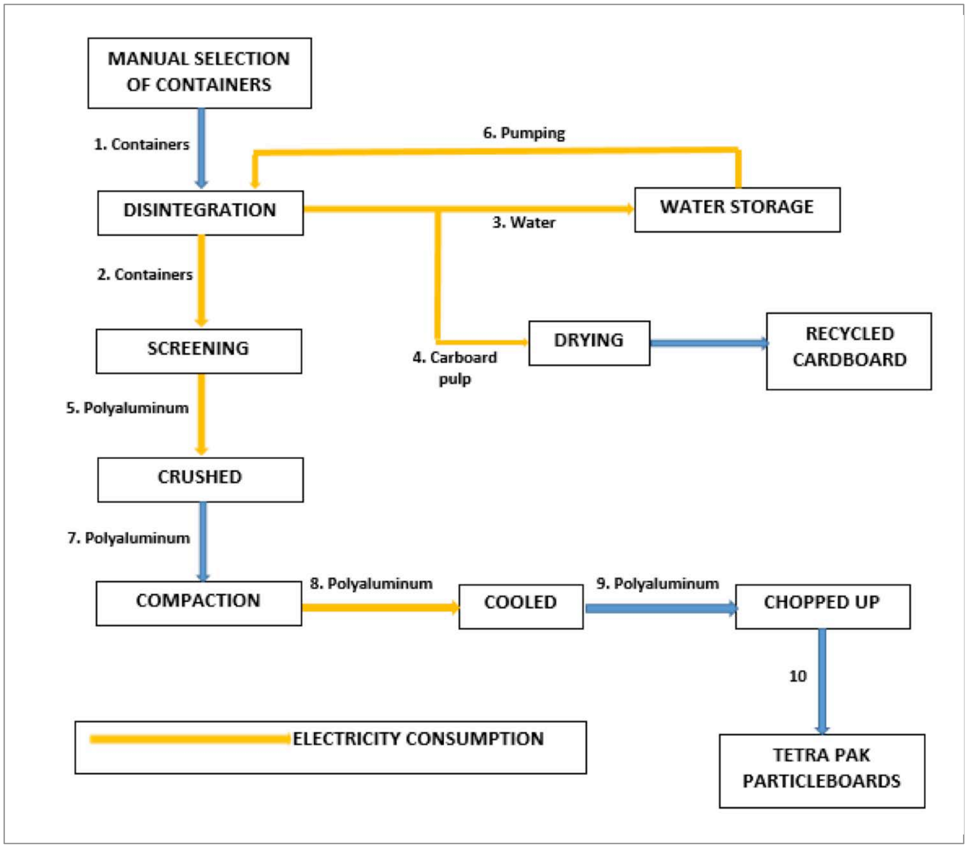


Figure 1. *Schematic production process for the RTPBB boards and later by-products*

Table 1. *Average mechanical parameters for the commercial RPTBB-ECOPLAK®, compared to wooden-based boards, and the minimum acceptance according to NTC-2261 Colombian standard R.-I. RIORION-Ltda. (2005)*

Parameter	Unit	Ecoplak ®	Wooden-Based	NTC 2261
Rupture Modulus	**MPa**	20	17,6	14,5
Elasticity Modulus	**MPa**	1,489	2,000	1,500
Bearing Perpendicular	**N**	726	1,100	550
Bearing Parallel	**N**	852	700	650
Maximum Humidity	**%**	4	5-6	6
Density	**Kg/m3**	1,070	600	>800

2. Materials and methods

Three types of specimens helped in understanding the basics of the material, and the structural response of main elements (beams and columns) built with RTPBB. Dog-bone specimens helped to obtain the basic stress-strain response in tension, while for the structural elements, specimens having 2m of length, 0.2m side of a square-hollow cross section, having a 15mm thickness wall, with two different construction systems. Testing of these specimens both in compression and in bending, helped to understand the two types of construction systems used, testing two types of board connection:

1. Mechanical Connection: 2-inch length (5cm) steel screws
2. Mechanical - Chemical Connection: 2-inch length steel screws + PL285 synthetic glue along edges

Additional RTPBB stiffeners placed at third points of both beam and column specimens helped to avoid lateral buckling of the unstiffened element members. The thickness of these stiffeners was as well 15mm.

Six monotonic (displacement controlled) tests on built-up beams and six built-up columns made of RTPBB, performed by a MTS dynamic actuator, followed a speed of 0.05mm/sec. until failure. Structural elements having a cross section of 0.20mx0.20m and a length of 2m were built using both, screwing (steel screws) and/or chemical bonding (industrialized glue) of custom-cut pieces, creating a hollow built-up structural element. When the element was no longer able to withstand any other increment of load (either in compression or in bending) or either cracking or buckling took place, then the test stopped. MTS sensors reported load and displacement from the information of the crosshead (applied load and displacement). Finite Element Models (FEM) of both RTPBB and wooden-based materials were useful to compare the resultant behavior for the same geometry used herein, with the test results obtained.

3. Stress-strain diagram of the RPTBB material

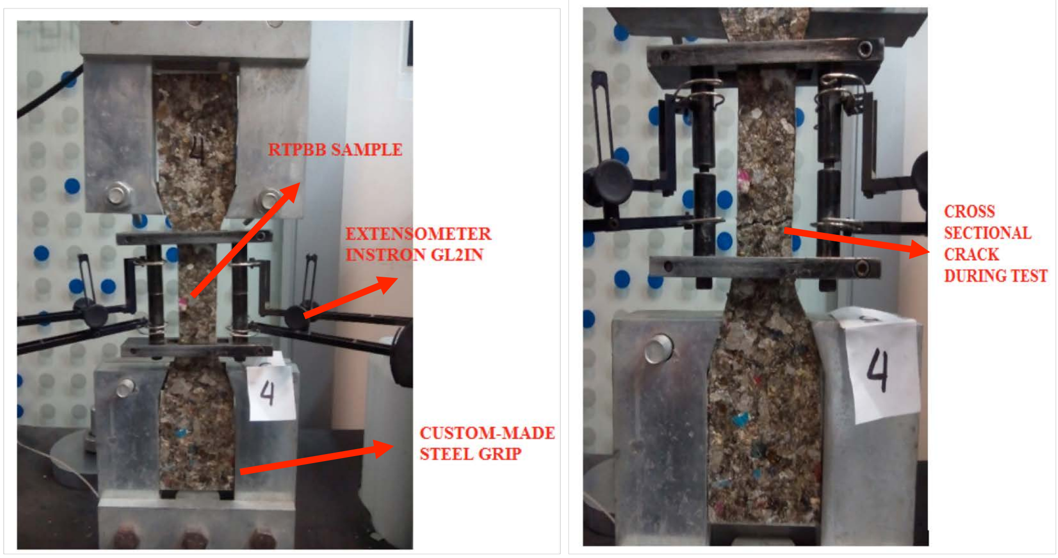
Even though average material data were available for RPTBB materials, a direct stress-strain test using dog-bone samples made of this material gave insights about its linear and non-linear behavior. For the test it was used a 3369 INSTRON Load Frame customized with a load cell of 50kN. The specimens used for the direct tension tests and the experimental setup for a typical failure are available in Figure 2. Results helped in determining the average modulus of elasticity, and in the finite element analysis simulation, including non-linear behavior of the material and large deformations.

4. Experimental Setup

For the bending tests, attached to the head of the MTS® actuator, a two-point load setup was the solution to apply load at the central third of the span of a simply supported beam (See Figure 3). This created a zone of pure bending which was the main objective of the test.

Table 2 and Table 3 show the code assigned to each specimen according to the type of connection used. Tests applied load at a rate of 3mm/min of crosshead displacement for both bending and compression. Both tests stopped when either two of the limit-states took place: excessive deformation or collapse.

For the compression tests, a simply supported pinned-end support was the main condition to apply the load trying to avoid as possible unaccounted bending. Figure 4 shows the specimen in compression. A prior check of the test was to avoid two-way initial out-of-straightness.



a) b)

Figure 2. *Direct tension tests to determine the stress-strain diagram for RTPBB material. a) Specimen under tensile test in an Instron ® 3369 Machine, b) Typical failure in tension*

Figure 3. *Specimen under bending tests using a central two-point load setup*

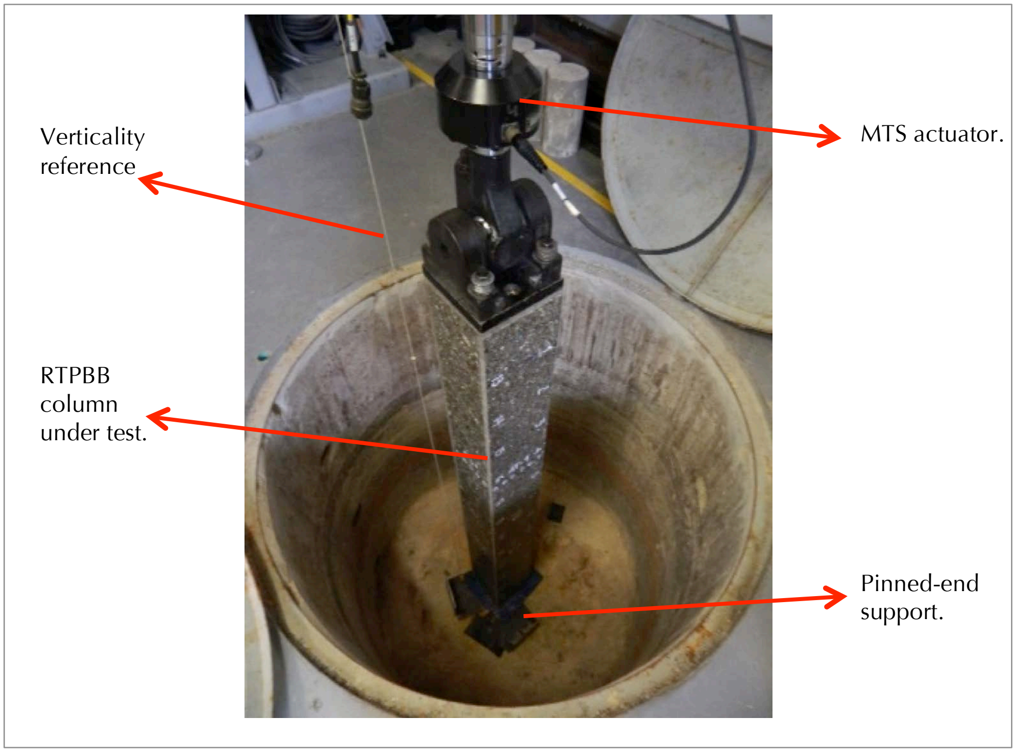


Figure 4. *Specimen under compression tests using simply supported conditions setup*

Table 2. *Specimen codes for bending tests*

	Connection Type	
ITEM	**Steel Screws**	**Steel Screws + Glue**
# Specimens	3	3
Code	vg-01, vg-02, vg-05	vg-03P, vg-04P, vg-06P

Table 3. *Specimen codes for compression tests*

	Connection Type	
ITEM	**Steel Screws**	**Steel Screws + Glue**
# Specimens	3	3
Code	C-01, C-04, C-05	C-02P, C-03P, C-06P

5. Results

Results are available in three parts: i) The stress-strain behavior of the material, ii) a visual record of the typical failure for the two types of loads applied, and iii) the record of data and corresponding analysis of the data obtained from the tests. After comparing results to the FEM models, showed fair agreement of the theoretical data with the experimental data.

5.1 Stress-Strain behavior of RTPBB base material

The stress-strain curve for one of the specimens shows a non-linear behavior with two initial linear behaviors. It is set a primary average modulus of elasticity E_{prim}*=747.2 MPa that lasts a strain range from 0.0002mm/mm to 0.000475 mm/mm, strain at which a secondary linear behavior is kept for a bigger range of strains (*E_{sec}*=238.02 MPa). The material (due to the nature of the particles within), does not have a yielding point. Rather it behaves nonlinearly until it reaches a maximum stress leading to rupture of the cross section with the advance of a perpendicular crack to the axis of load (See Figure 2, part b). Data is available Table 4.*

Table 4. *Modulus of elasticity (primary and secondary), for the RTPBB material*

	Modulus of Elasticity RTPBB	
Test	Primary (MPa)	Secondary (MPa)
1	719.23	181.94
2	765.85	296.96
3	756.50	235.18
Mean Value	747.19	238.02
Standard Deviation	24.66	57.56
C.O.V.	0.033	0.241

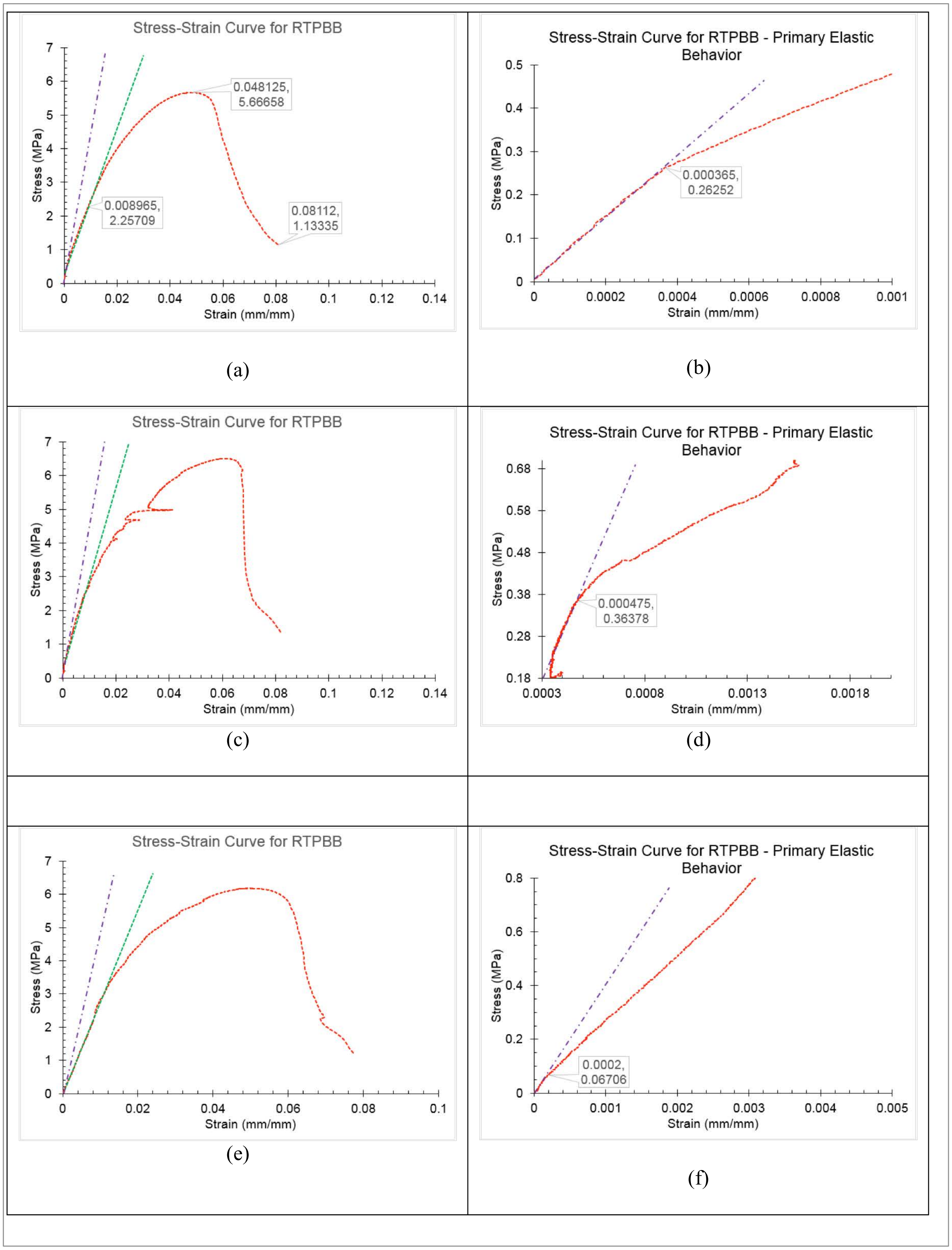


Figure 5. (a) Test No. 1 Stress- Strain curve, (b) Test No. 1 Primary elastic behavior, (c) Test No. 2 Stress – Strain curve, (d) Test No. 2 Primary elastic behavior, (e) Test No. 3 Stress – Strain curve, (f) Test No. 3 Primary elastic behavior

5.2 Typical failure for elements under bending

Specimens subjected to bending failed mostly because of the propagation of a crack that originated in the zone where the lateral board is present (perpendicularly to the stiffener). Specifically, the crack initiated at the hole created by the steel screw. Typical crack and final deformed stage for the specimens are in Figure 6.

5.3 Typical failure of elements under compression.

The main failure of these elements was local buckling in the lateral boards of the column. Although a third-point RTPBB stiffener was present, the remaining unsupported distance was large enough to make these elements weak to buckling. After said elements reached this limit state, columns lost their loading capacity due to the formation of instability mechanisms. A buckled specimen is in Figure 7. Although buckling is supposed to be an elastic problem, by the time the test stopped, the buckling of the unstiffened element was present along with the advance of cracks in tension.

a) b)

Figure 6. *a) Hollow RTPBB-structural element typical crack beginning in a lower screw, b) Final failure stage for the beam, where crack advances into compression side of the lateral board*

a) b)

Figure 7. *a) Lateral board buckling at mid height of the specimen under compression, b) Final buckling stage for the two unstiffened elements*

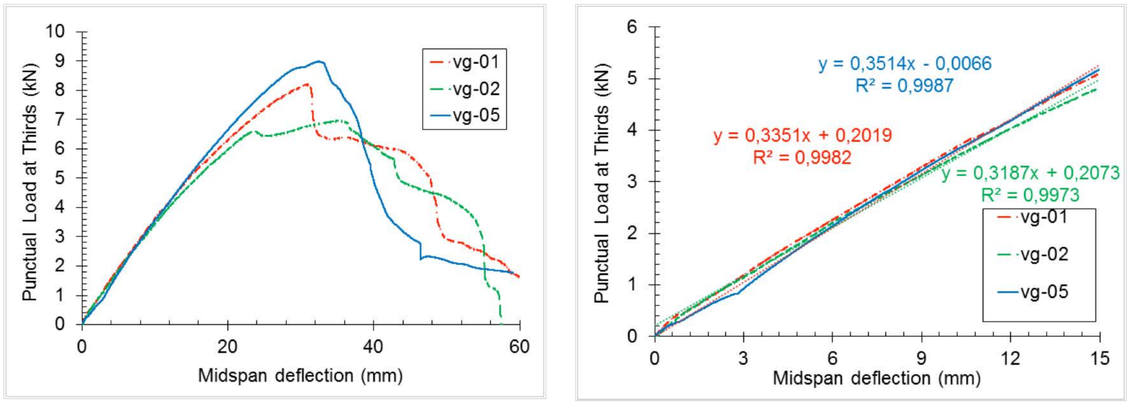
5.4 Results for RTPBB structural elements under bending

Load and displacements were direct readings obtained from the MTS sensors. A plot of said variables for the three specimens of each type of connection are in Figure 8 and Figure 9. Two main behaviors are present for the recorded data: i) an initial linear behavior and ii) an instability behavior with non-linear components before and after reaching the maximum load. The non-linear behavior after the maximum load however, seems to be chaotic and suggests a semi-brittle failure of the structural member, representing the fast-crack advance observed in Figure 6 part b.

Results presented in Table 5 are for the specimens under bending using exclusively steel screws as joining element of the various pieces made of RTPBB. In the cases tested, the maximum deflection was the result of material cracking advance, with a coefficient of variation of 0.018.

Figure 9 shows the behavior of the RTPBB beams joined together with steel screws and PL285 industrial glue. Although the behavior is not as stable during the linear part of the behavior of this material, it still resembles the first set of specimens tested.

Maximum loads and deflections shown in Table 6 are for the specimens under bending joined using steel screws and PL285 glue along the edges of the connecting members.

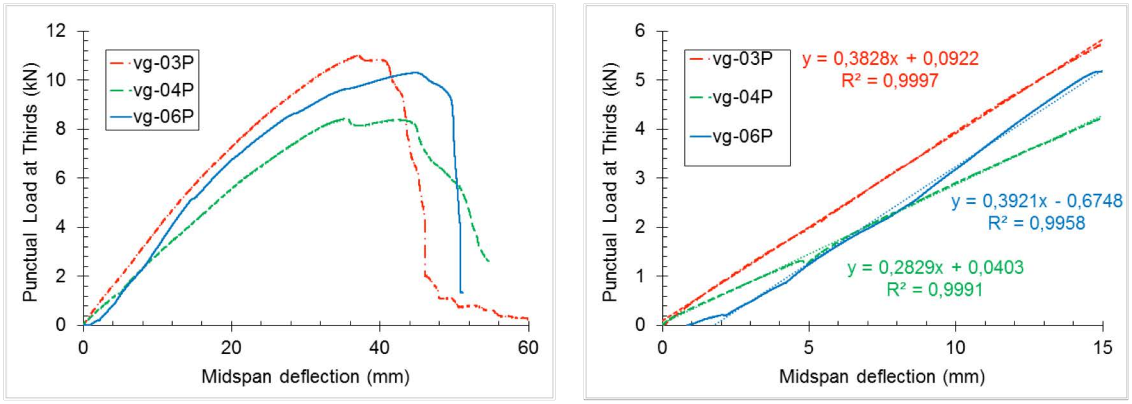


a) b)

Figure 8. *Load vs displacement plot for the specimens under bending using exclusively steel screws as joining element. a) Complete behavior of test, b) Linear behavior of the three specimens under test. The slope is similar for the three specimens*

Table 5. *Maximum load and deflection for beams made of RTPBB joined with steel screws exclusively*

Beams joined with steel screws exclusively			
No.	**Maximum Load (kN)**	**Indirect Toughness (kN-mm)**	**Maximum Deflection (mm)**
vg-01	8.20	285.89	59.99
vg-02	6.96	272.41	57.77
vg-05	8.98	222.04	59.10
Average	8.05	260.11	58.95
Std.Dev	1.021	33.65	1.12
COV	0.126	0.129	0.018



a) b)

Figure 9. *Load vs displacement plot for the specimens under bending using steel screws and PL285 glue type. a) Complete behavior of test, b) Linear behavior of the three specimens under test. The slope in this case is only similar for tests vg-03P and vg-06P*

Table 6. *Maximum loads and deflections for RTPBB beams joined with both steel screws and PL285 glue type*

Beams joined with steel screws and PL285 glue type			
No.	**Maximum Load. (kN)**	**Indirect Toughness (kN-mm)**	**Maximum Deflection (mm)**
vg-03P	11.00	331.79	59.99
vg-04P	8.43	228.87	54.61
vg-06P	10.30	309.14	51.18
Average	9.91	289.93	55.26
Std. Dev	1.33	54.08	4.44
COV	0.134	0.186	0.080

In Table 5 and Table 6, the coefficient of variation has a maximum of 0.186 for loads and displacements. Also, tables indicate that for elements made of RTPBB in bending, the addition of PL285 glue type as a complementary means of connection, improved a total of 23.1% the maximum load reached for failure. The effect was not true for collapse deflections reducing its magnitude a 6.26%.

With the available data, an estimation of two complementary parameters, average ductility -Ω*- (Eq 1), and an indirect average measurement of toughness (Eq. 2) is possible. These parameters were important to compare between the two types of connections used to create the built-up sections. Results of said parameters are available in Table 7. A definition of ductility is:*

$$\Omega = \frac{\Delta_{max}}{\Delta_{elastic}} \qquad \textbf{\textit{(1)}}$$

where Δ_{max} corresponds to the maximum deflection at which the element collapsed, and $\Delta_{elastic}$ corresponds to the deflection at which the primary linear behavior was lost.

For the case of indirect toughness, the estimation comes from the numerical solution of the integral:

$$\boldsymbol{\zeta = \int_0^{\Delta_{max}} P(\Delta_i)\, d\Delta_i} \qquad \textbf{\textit{(2)}}$$

where $P(\Delta_i)$ corresponds to the curve that describes load change as a function of displacement.

Table 7 shows how beams built with steel screws and PL285 glue had an improved toughness, in part for the higher load achieved. However, the linear zone of the response of the material is shorter in beams that used both steel screws and glue. In other words, the stiffening behavior that glue brings to the structural member seems to affect the relationship between elastic and maximum deflections.

Deflections along the length of the hollow-structural RPTBB FEM were a representation of color contours as seen in Figure 10.

Table 7. *Summary table of additional parameters obtained from the bending tests for the two types of beams*

ITEM	Beam with Steel Screws	Beam with Steel Screws+PL285
Maximum Load of all tests (kN)	8.98	11.00
Maximum Deflection (mm)	59.99	59.99
Average Ductility - Ω	3.74	2.98
Highest Indirect Toughness - ζ (kN-mm)	285.89	331.79

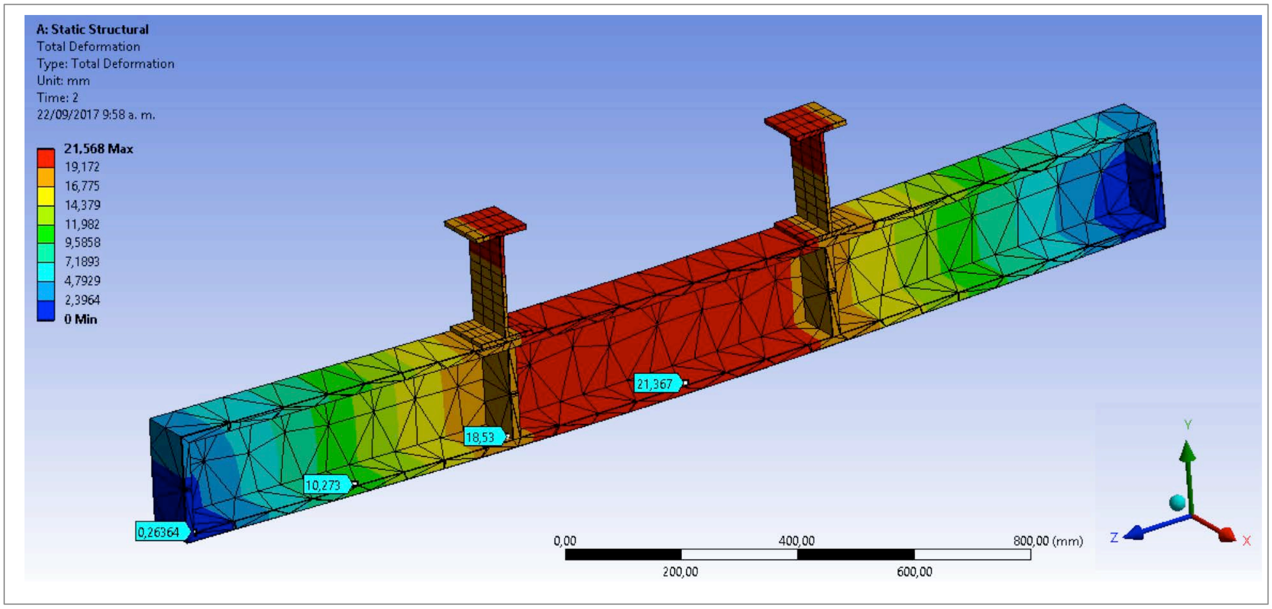


Figure 10. *Deflections along the beam, for a FEM of the experimental beam used (stiffeners shown). Maximum deflection according to the model is of about 21.56. Units in mm*

5.5 Results for RTPBB structural elements under compression

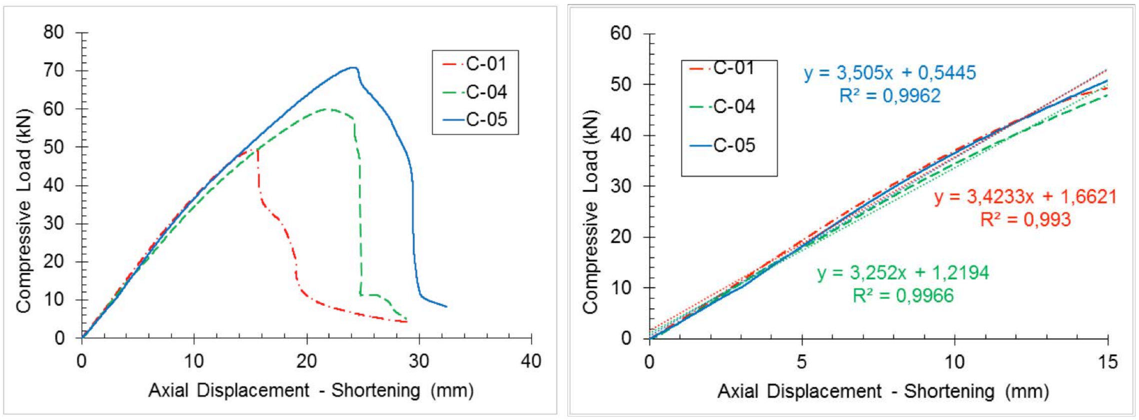
Similarly, loads and deflections recorded for the built-up elements under compressive loads for the two types of connections used, show differences in the tests done. Figure 11 and Figure 12 present the results with a semi-brittle behavior compared to those for the elements under bending.

Slopes of the linear behavior in Figure 11 part b, represent a predictable linear behavior in the case of columns that were built only with the use of steel screws. In all cases tested, after reaching a mean peak load of 49.37kN (with a C.O.V of 0.0293) – See dotted oval in Figure 11 b)- , the structural component ceased to behave linearly.

Similarly, the behavior in Figure 12 part b, represents a predictable linear behavior in the case of columns that were built with the use of steel screws plus PL285 glue. For the tests performed, after reaching a mean peak load of 42.27kN (with a C.O.V of 0.0884) – See dotted oval in Figure 12 b), the structural component ceased to behave linearly. However, for tests C-02P and C-03P, a semi-linear behavior extends until a peak load above 55kN.

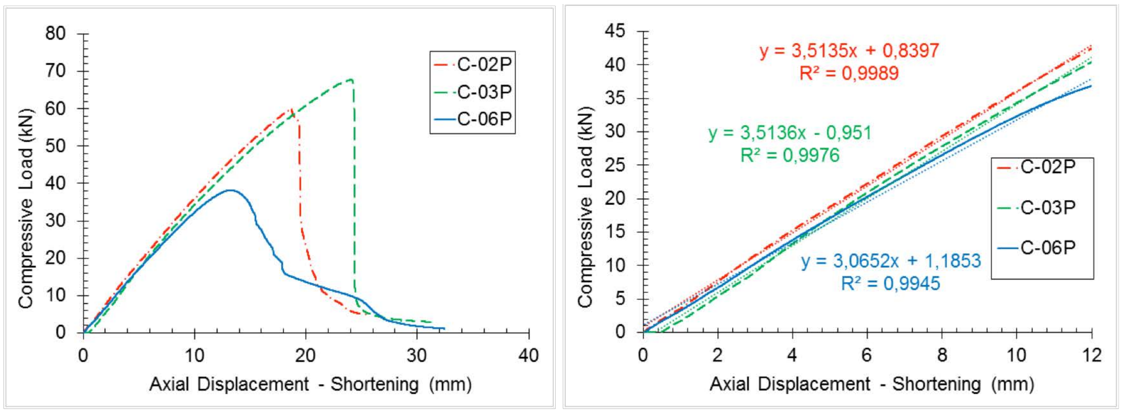
The previous curves show a relatively similar behavior for the two types of specimens. These structural elements in compression have a semi-brittle behavior, mostly due to the buckling of the unstiffened elements (See Figure 7). In addition, there is almost no effect on the capacity of the built-up columns when an industrial glue (PL285 type) works together with steel screws. In fact, data in Table 9 and Table 10, show a detrimental behavior of members joined with said elements.

Although a different bonding system was present for the two types of columns, the linearity of the behavior of the structural elements in compression (load vs displacement graph), was similar in both cases according to the slopes of the best-fit linear models of the experimental data (See Table 8).



a) b)

Figure 11. *Load vs displacement plot for the specimens under compression using exclusively steel screws as joining element, a) Complete behavior of test, b) Linear behavior of the three specimens under test. The slope is similar for the three specimens*



a) b)

Figure 12. *Load vs displacement plot for the specimens under compression using steel screws and PL285 glue type, a) Complete behavior of test, b) Linear behavior of the three specimens under test. The slope is similar for the three specimens*

Similarly, the behavior in Figure 12 part b, represents a predictable linear behavior in the case of columns that were built with the use of steel screws plus PL285 glue. For the tests performed, after reaching a mean peak load of 42.27kN (with a C.O.V of 0.0884) – See dotted oval in Figure 12 b), the structural component ceased to behave linearly. However, for tests C-02P and C-03P, a semi-linear behavior extends until a peak load above 55kN.

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As presented in Table 9 and Table 10, the COV ranges between 0.177 and 0.276. This suggests that construction detailing and possible initial out-of-straightness might be source deviators for the load capacity of these specimens.

***Table 8.** Slope of the linear behavior for RTPBB elements under compression. The C.O.V of 0.0543 represents a stable linear behavior for the two types of joining systems tested*

Test ID	Slope of the Best-Fit Linear Model (kN-mm)
C-01	3.423
C-04	3.252
C-05	3.505
C-02P	3.513
C-03P	3.513
C-06P	3.065
Mean (kN-mm)	3.378
Standard Deviation (kN-mm)	0.1835
Coefficient of Variation	0.0543

***Table 9.** Maximum load and shortening for columns made of RTPBB joined with steel screws exclusively*

Columns joined with steel screws exclusively			
No.	**Maximum Load. (kN)**	**Maximum Load (Ton)**	**Shortening (mm)**
C-01	49.56	4.95	28.91
C-04	59.93	5.99	28.82
C-05	70.88	7.08	32.43
Average	60.12	6.01	30.05
Std. Dev	10.66	1.06	2.06
COV	0.177	0.177	0.068

***Table 10.** Maximum loads and shortening for RTPBB columns joined with both steel screws and PL285 glue type*

Columns joined with steel screws and PL285 glue type			
No.	**Maximum Load. (kN)**	**Maximum Load (Ton)**	**Shortening (mm)**
C-02P	60.18	6.02	25.33
C-03P	67.71	6.77	31.89
C-06P	38.23	3.82	32.39
Average	55.37	5.53	29.87
Std. Dev	15.31	1.53	3.94
COV	0.276	0.276	0.132

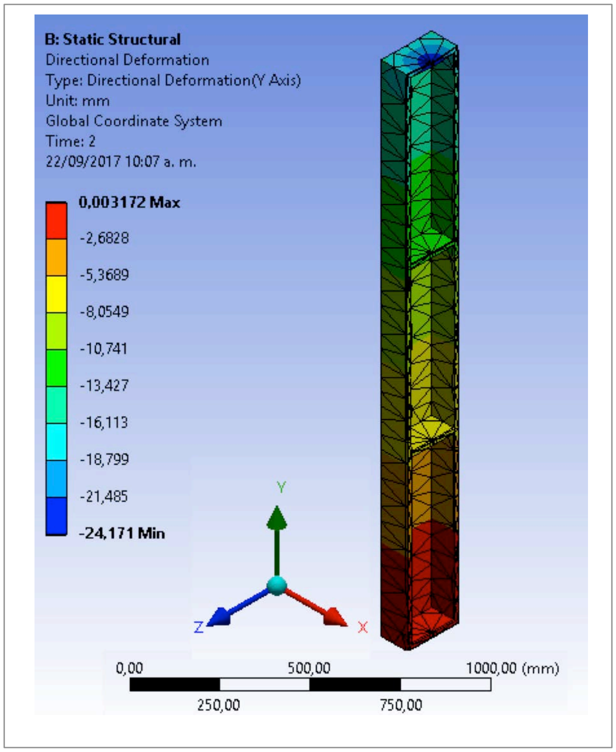

Figure 13. *Compressive shortening in a FEM for RTPBB structural elements. Maximum experienced shortening is 24.17mm*

6. Functional Unit Definition for carbon footprint approximated calculations in wooden-made and RTPBB-made elements

For the carbon footprint calculations, the functional element defined, followed the main geometry of the built-up elements tested in the present research. The total volume of material involved according to the geometry of the specimens is of about 0.0264 m^3. The same volume applies regardless of the material used (wood or RTPBB). However, as densities of both materials under discussion are different, a relation coefficient is set for further calculations. For the RTPBB specimens, with a density of about 1070 Kg/m^3, the total material mass is of 28.25Kg, and for comparable wood elements (not built for the present research) with a density of about 600 Kg/m^3, the total material mass would be of 15.84 Kg. Thus, the relation coefficient is 0.56 RTPBB/wood.

7. Discussion on the modeled deflection results vs test deflection results

Taking the primary modulus of elasticity (E_{prim}) reported herein, and creating a FEM of the beam that was tested, results in an approximated deflected geometry of the structural member. A FEM model was better instead of a frame element model, because of the hollow cross-section. In addition, to account for the stiffeners provided at thirds of the span. Results of the maximum deflection for the maximum load recorded during the tests (See Table 7) of 60mm is bigger than the deflection reported by the FEM models.

When E_{prim} is used, the FEM reports a maximum deflection for beams of 21.56 mm assuming that the load will keep the structural element within elastic ranges However, if it is used the modulus of elasticity reported in Table 1 the deflections are of about 6.8mm. This shows how the modulus of elasticity found in the present research suits better (when used in FEM to obtain better agreement with experimental deflections data

As done with beams, FEM for compression helped to compare which modulus of elasticity was the one modeling better the structural element behavior observed in the laboratory. For the comparison it was used a compressive load of 70.88kN. Results show that for mechanical parameters suggested in Table 1, the maximum shortening experienced by the model is of about 8.46mm. However, when the modulus of elasticity obtained in the present research was account in the model, the shortening becomes 24.17mm. Still smaller than the experimental shortening of 32.43mm, it approaches better the order of magnitude (74.52% with respect to experimental).

Additionally, as a basic comparison of resultant stresses and deflections on beams and columns made with RTPBB and wooden-based materials, FEM models were loaded in the same way (with the highest loads), and cross sectional members maintained. However, self-weight and modulus of elasticity are different (See Table 1) which result in different structural behavior. Results for simulated columns and beams made with these two materials are in Table 11 and Table 12.

Results of these basic FEM´s suggest that modeled stresses in RTPBB elements are similar to those if the structural elements were wooden-based materials. However, the deflections are different due to the elasticity modulus and variations in the weight per cubic unit.

8. Approximated environmental impact of wooden-made and RTPBB-made structural elements

In terms of fabrication efforts, it is easier to do a board of RTPBB material rather than wooden-based boards, specifically due to the amount of raw materials involved and the number of sub-processes. Thus, to make these wooden-made particleboards competitive with RTPBB, raw materials must go down. A study done in Spain proved the environmental benefits of replacing raw wood by percentages of recycled wood into the process of creating wooden-based boards Saravia-Cortez et al. (2013). To produce an element of RTPBB, phenolic resins are not necessary as in the case of the wooden-made boards. This is a substantial positive environmental characteristic, especially because phenolic resins are pollutants classified by many environmental entities such as the United States Environmental Protection Agency - USEPA and the Center for Environmental Education CEE. Specifically, a study proved how the degradation rate of said pollutants increases only with higher levels of water temperature or the presence of certain controlled catalysts Wang et al. (2011), making a demanding task to remove phenolic compounds from water.

In Colombia a total of 712 Ton of TetraPak® containers were recovered from solid waste in 2014, which means that the potential use of RTPBB as construction material, can lower the amount of solid waste going directly to landfills. In addition, the electric consumption needs to be accounted for board shaping. According to a study of the consumables in the production of these type of boards, the average electric consumption of an electric saw is about 0.11 KWh/m^2 for shaping the boards dos Santos et al. (2014). The surface area of the beam element used in this research is 1.76 m^2. Thus, the total energy consumption to shape the beam from raw boards is about 0.1936 KWh.

Using the density and the total amount of material needed to construct a structural element, and based on average consumption rates of gas, electricity and water, the following table is a summary of general raw material consumption, for the same functional unit. (Table 13)

Table 11. *Maximum deflection and induced stresses on FEM beam models keeping the hollow geometry used in the present research*

Material used for the FEM Beam	Bending Stress σ_{max} (MPa)	Shear Stress τ_{max} (MPa)	Maximum Mid-span Deflection (mm)
Wooden-made Board	1.65	0.23	6.93
RTPBB Board	1.63	0.41	57.8

Table 12. *Maximum shortening and induced stresses on FEM column models keeping the hollow geometry used in the present research*

Material used for the FEM Column	Compressive Stress σ_{max} (MPa)	Shear Stress τ_{max} (MPa)	Maximum Shortening (mm)
Wooden-made Board	7.50	0.27	6.32
RTPBB Board	9.37	0.14	52.8

Table 13. *Total resources quantity used to construct one functional unit used in this research*

RAW MATERIALS NEEDED TO PRODUCE A FUNCTIONAL UNIT			
Material	**Gas (m^3)**	**Electricity (KWh)**	**Water (m^3)**
Wooden-made Board Structural Element (15.84 Kg)	2.26	2.97	0.44
RTPBB Board Structural Element (28.248 Kg)	0.37	11.58	1.13

According to Table 13, the net fabrication of a built-up structural element as the ones used for the specimens of this research uses an 83.57% more natural gas, but at the same time with a 74.39% less electric consumption compared to RTPBB. In the case of water consumption, the wooden-made structural elements require 60.9% less water than RTPBB elements for their construction.

If for each Ton of recycled TetraPak® material, production saves an approximated total of 26,500L of water, then for the functional unit of the present research, production saves 748L. Thus the real consumption would not be 1.13m^3 H_2O/structural element; rather a consumption of only 0.377m^3 H_2O/structural element would be the real consumption.

Using the emission factors reported by the University of Santader of Colombia U. de S.- UDES (2012) which are summarized in Table 14, an approximated carbon dioxide emission is reported for each functional unit (wooden-made and RTPBB-made), and presented in Table 15. Thus, to produce a structural functional unit of RTPBB saves 1.04Kg de CO_2 compared to wooden-made materials.

Results in Figure 14 show in percentage the most important sources of CO_2 footprint for each one of the functional units of RTPBB and wooden-made materials. The water saved in each case makes the difference in the analysis. The fact that for RTPBB material recycling is the main source of this material makes an overall smaller CO_2 footprint. The total CO_2 footprint for each of the material's functional unit is available in Figure 15.

Table 14. *CO_2 equivalent factor per consumed resource*

Consumable	Quantity	Emission Factor (kg of CO_2)
Gas (m3)	1	1.88
Electricity (kW/h)	1	0.29

Table 15. *Total carbon footprint for each material's functional unit*

TOTAL CARBON FOOTPRINT (Kg of CO_2)			
Material	**Gas**	**Electricity**	**Total**
Wooden-made Board Structural Element (15.84 Kg)	4.25	0.86	5.12
RTPBB Board Structural Element (28.248 Kg)	0.69	3.35	4.04

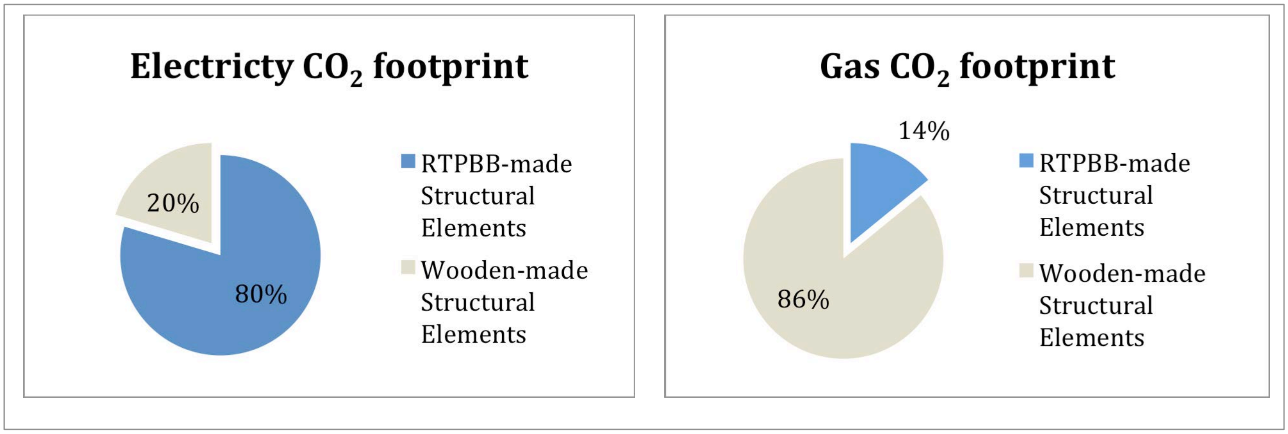

Figure 14. *Electricity and gas carbon dioxide footprint, comparing the fabrication of a functional unit (beam or column)*

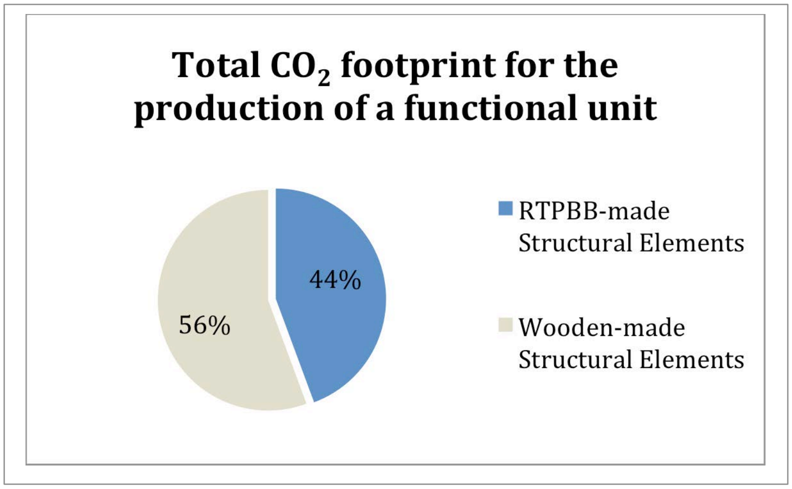

Figure 15. *Total CO$_2$ footprint for each material's functional unit*

9. Conclusions

- *A set of specimens showed the capacities of hollow structural elements made of RTPBB material under compression and tension. Results showed the capacity of these structural elements in each case, also showing a linear behavior followed by a limited non-linear behavior, which is smaller in the case of columns due to unstiffened elements.*
- *Although third-point span stiffeners made integral part of the hollow structural element to avoid lateral torsional buckling in the case of elements under bending, or lateral buckling of unstiffened elements in the case of elements under compression, the stresses and geometrical instabilities found their inception in said elements.*
- *For the specimens in bending, the type of board connection was influential in the structural response, in terms of deflection and maximum loads. Thus, for specimens that utilized steel screws and PL285 glue type, it improved their load capacity in average a 23.1%. However, it reduced a 6.67% for maximum deflections with respect to specimens that used only steel screws.*
- *Cracks in bending found their inception at discontinuities such as the holes created for steels screws to join boards perpendicularly. Said crack advanced along the lateral board, and went through the compression side of the beam (See Figure 6). The later because the particles of the material are big in size, and thus are not good elements to arrest the advance of the crack. It is recommended to use a bigger number of steel screws along the edge to join the boards, and to pay special attention to placement, as if screws are too close to the edge, it is detrimental for the structural beam.*
- *Comparing the toughness of both systems of construction of specimens under bending (See Table 7), the use of steel screws and PL285 glue improved also structural capacity. This, because loads need to remove the bond among glued faces in addition to the shearing of the material as the crack advances. However, in the case of specimens under compression that improvement was not present. The previous suggests that the buckling effect is important in these structural elements. An advice to address a tougher column is the use of additional intermediate stiffeners (fifths or sixths of span). Bigger number of stiffeners will shorten the unsupported length of the board, and will improve overall capacity.*
- *According to the results of the FEM models when comparing wooden-made and RTPBB-made elements, the stiffness of wooden-made structural elements is bigger. This because the modeled deflections in bending and the shortening in compression are both smaller in comparison with the RTPBB-made structural elements (Table 11). This matches the difference in the elasticity modulus between materials. However, comparable stresses make the structural behavior comparable and suggest that structural elements made of RTPBB can also work as structural elements of a well-known material as the wooden-based boards.*
- *From the materials needed to produce a functional unit (same for the bending specimens and the compression specimens), the consumption of gas and electricity is smaller for RTPBB materials than for wooden-made materials (Table 13). However, water consumption is higher. If, the water saved during recycling is accounted, then the consumption of water to produce RTPBB structural elements drops to competent quantities with respect to wooden-made ones.*
- *The carbon footprint of producing a functional unit of wooden-made material presumably is 26.7% larger than the one for producing a functional unit of RTPBB-made material. This because the carbon*

footprint of gas consumption is larger than the one for electricity or water consumption.

- *Results open the possibility for constructors to use this material in specific parts of a project, bringing the use of a material with competent mechanical capacity compared to wooden-made materials, but with the benefits of a lower carbon footprint. Applications can be direct in the case of one-story houses, temporary housing or temporary shelter for catastrophic events where the demand of houses can happen in short time.*

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